Liquefaction resistance of fibre-reinforced silty sands under cyclic loading

Soheil Ghadr[1*], Alireza Samadzadeh[2], Hadi Bahadori[3], Arya Assadi-Langroudi[4]

[1*][Corresponding Author] Ph.D., Civil Engineering Department, Urmia University, Urmia, Iran
Tel: +98901 510 8968; Email: s.ghadr@urmia.ac.ir
[2] MSc, Civil engineering department, Urmia University, Urmia, Iran
Email: st_a.samadzadeh@urmia.ac.ir
[3] Associate professor, Ph.D., Civil engineering department, Urmia University, Urmia, Iran
Email: h.bahadori@urmia.ac.ir
[4] Engineering and Computing, University of East London, Royal Docklands, London, UK
Email: a.assadilangroudi@uel.ac.uk

Abstract

Whether the so-called double porosity in soils with a loose and natural packing state is a concept with real-world implications is a fundamental yet controversial question in the study of cyclic undrained shear behaviour of fibre-reinforced silty sands. An attempt is made here to clarify the question by means of particle-level modelling combined with 41 undrained cyclic triaxial shear tests. The study shows that the initial Random Loose Packing changes to Random Close Packing and then Close Packing with silt content increments. The transition from random to close packing occurs at a threshold silt content which is relatively lower in coarser sands. For sands with <40% silt content, the rate of pore pressure growth with loading-unloading cycles increase with silt content increment. Reverse trend applies to silty sands with >40% silt content. Irrespective of fine content, fibres tend to sit deep into the silt pellets and encrust the macro-pore spaces. Generally, increasing fibre content leads to an increase in the average number of contacts per particle, dilation and easier dissipation of excess pore water pressure, a decrease in contact forces and improved liquefaction resistance. For sands with >40% silt content, effectiveness of fibre reinforcement diminishes with increasing sand median size.

Keywords: Liquefaction; silty sand; fibre; cyclic; shear; packing

1. Introduction

For a traffic infrastructure (e.g. roads, highways, railway tracks) constructed on low embankments or built directly on sandy grounds, the compressibility of the subsoil has substantial effects on the stability, operational speed (i.e. serviceability) and the maintenance costs of the system. Deformation of the subsoil is dependent on their strength and stiffness, as well as applied loading conditions. Subsoils under static loading fundamentally behave differently than subsoils under repeated traffic loading of the same order of magnitude. Depending on the magnitude of the individual wheel load, and the number and frequency of repetitions, subsoils may experience excessive deformations and in some cases liquefaction and flow. Liquefaction is the substantial loss of strength in soil in response to a sudden change in stress state mostly caused by earthquake and seismic loads (for example from the inertia loads in onshore wind turbines during emergency stop), but also traffic loads (Wichtmann et al. 2004) and loads associated with high-speed moving vehicles (Naeini and Gholampoor 2014). Liquefaction is mostly expected in loose saturated clean sands although it may also occur in clayey and silty sands. In principle, soil liquefies as the excess pore water pressure reduces the effective stress to dangerously low levels, leading to catastrophic floating (Sawicki and Mierczyński 2015), sinking of structures (Ardeshiri-Lajimi et al. 2016) and ground subsidence (Romeo et al. 2015). For traffic infrastructure, elevated levels of excess pore water pressure have adverse impacts on the operational speed and stability of the system, regardless of liquefaction. In the short term, liquefaction is unlikely to occur in dense granular soils. In the long term, at shallow depths and under certain combinations of temperature, soil suction, soil permeability, and availability of water, weathering and subsequent particle-level events can lead to the development of new open structures in soil (Li and Selig 1995), thereby a potential of liquefaction. This 'progressive loosening' problem is more common in finer soils and upon the progressive flow of fines and softening (Ghadr and Assadi-Langroudi 2019), or dilation associated with strain softening (Indraratna et al. 2011). The effect of fine fraction and reinforcement element (e.g. fibre) content on liquefaction resistance of soils have received much interest but the studies are constrained to granular mixtures compacted to a constant and high relative density. Little is known on the cyclic behaviour of relatively loose silty sands in reinforced and natural forms and compressed to their natural random packing state. The aim of this paper is to show to what extent the cyclic response of loose sands compares with that of the loose sand-silt and sand-silt-fibre mixtures and to provide evidence to the influence of some packing parameters of the materials on fibre-reinforced soils' mechanical response.

1.1 Progressive Loosening: Rationale

In the long-term, sand-silt mixtures progressively develop a quality of open porosity that can cause uncertainties in serviceability of the built settings they underpin. Such unwelcomed implications are generally overlooked in the literature and have motivated this study. Khosravani (2014) and Assadi-Langroudi (2014) modelled loosely packed cemented silty soils in the form of three-phase discontinuous mediums composed of sub-rounded. Mono-dispersed, silt particles of R diameter bridged with water menisci and bonding minerals. They adopted a homogenization framework, taking the soil system as a representative elementary volume (REV) composed of particles that interact with one another via a suite of traction forces ($t_i(x)$), and expressed the effective stress as a function of local micro-scale variables. Khosravani (2014) derived a the tensorial form of the effective stress equation as a function of χ_{ij} and B_{ij} effective stress parameters, and expanded the formulation for the benchmark REV. She assumed that the continuity of the pore network is a valid simplification regardless of soil's structure and its dependence on the matric suction. For cemented Body-centred Cubic (BCC) regular packings, Assadi-Langroudi (2014) used the double-porosity theorem and proposed an improved form of the tensorial effective stress equation and suggested that the B_{ij} the parameter is inversely proportional to χ_{ij} (the Bishop property) and is a direct function of σ_{ij}^{d}, a periodic hydro-dynamic boundary level stress acting on buttress units during the flow of liquid between micro- and macro-pore phases.

In this, Khosravani (2014) and Assadi-Langroudi (2014) formulated the inter-particle forces acting at contact points which at macro-scale represents the effective stress, σ'_{ij}, that applies to the solid skeleton in a soil. The water influx into loose lightly bonded granular assemblies initially impacts the buttress units.

Upon full saturation of buttress units, pore water advances into the macro-pore spaces. As the matric suction drops below the air entry value, air pockets relocate from macro-pores into micro-pores within the buttress units. In fact, macro-pore air begins to dissolve in micro-pore water before the influx of water into the macro-pore voids. This leads to the collapse of buttress units into macro-pore spaces and their coagulation. Upon drying, the macro-pore phase lose water while the σ_{ij}^{d} remains at its nominal minimum. Under constant net stress and matric suction at micro-pore level, $(u_a - u_w)_m$, and in the absence of an immediate head gradient between micro- and macro-pore phases, effective stress decreases, resulting in a rebound volume change and expansion. Assadi-Langroudi (2014) showed that this progressive volumetric expansion under constant net pressure continues over subsequent wetting-drying cycles. In the long-term, this induced open structure in engineered silty sands can cause uncertainties in serviceability of the built settings they underpin, a matter which has been broadly overlooked in the literature.

1.2 Question of Packing

In the terrestrial system, sand is fundamentally a binary particulate matter (Yamamuro and Lade, 1999) and almost always comprises an inherently crushable quartz silt fraction (Assadi-Langroudi et al. 2014). The physical nature and mechanical response of sand are dependent on its silt content (Lade and Yamamuro, 1997; Thevanayagam et al. 1997; Thevanayagam,1998). Yamamuro and Covert (2001) discussed the effect of silt fraction variation on soil packing state. In their pivotal work, they proposed three transitional zones and three extreme packing states that can theoretically appear in any sand-silt composite (identified as points labelled as A, B and C in Fig. 1).

Figure 1. The schematic explanation of packing for sand-silt composites (Yamamuro and Corvet, 2001)

In a binary mixture of particles with two sizes, and where the fines content is low, fine matters tend to sit in macro-void spaces between larger particles. An increase in fines content leads to an increase in the packing density, causing particles to be more closely 'knitted' together (Fonseca et al. 2013). Yamamuro and Covert (2001) suggested that the packing density reaches the maximum at a critical threshold fines content of around 20% (by weight). For the fine matter to fit into macro-voids, the diameter of the fine particles should be at least 6.5 times smaller of the large particles. Further increment of fines content (from 20 to 50%) leads to a decrease in packing density as the fine fraction begins to push the larger particles apart, separate the large particles and cause the increment of global void ratio until the volume of fine particles become large enough to accommodate larger particles as isolated inclusions (Xenaki and Athanasopoulos, 2003; Chang et al. 2015).

Sladen et al. (1985) showed a decrease in strength of sand for the addition of small contents of non-plastic silt. Pitman et al. (1994) argued these findings based on findings from a programme of undrained triaxial compression tests on the standard Ottawa Sand. For soils with up to 40% silt content, they showed an increase in the strength of Ottawa Sand that mitigates the rapid shearing-induced collapsibility typically appearing in clean sands. Verdugo and Ishihara (1996) presented experimental evidence for the contractive response of silty sands, and consequently the high risk of flow failure and liquefaction. The dispute over the role of silt in mechanical behaviour of sand continued into the 21st century, and emphasis was put on the interplay between silt content and packing quality, and also the complex mechanics of binary mixtures (Bouckovalas et al. 2003; Thevanayagam and Martin, 2002; Xenaki and Athanasopoulos, 2003; Yang et al. 2006; Yin et al. 2014). Lade et al. (2009) studied the role of fine fragments in the formation of highly compressible, liquefiable microstructures in sands. Monkul (2013) downplayed the importance of fines content, and sand and silt gradation quality on strength parameters. Studying the cyclic behaviour of silt and sandy silt soils, El Takch et al. (2016) presented evidence in support of susceptibility of non-plastic silts to liquefaction and similarities between the strain and excess pore water generation patterns in sand and silt under dynamic excitation. They also suggested that the cyclic stress ratio (CSR, or the ratio of the cyclic deviator stress to the initial confining stress) increases with increasing silt content at constant global void ratio (also see Noorzad and Amini 2014; Karim and Alam 2014). The majority of published research is based on experimental works on soils compacted to a constant low void ratio. Little is known on the cyclic response of loose saturated silty sands with a naturally open structure. This, together with the oftencontradictory perception of fines influence on the cyclic behaviour of granular soils have led to broad uncertainties in cyclic properties of composite granular geomaterials and their dependence on packing quality of constituting particles.

In this, the macro-scale cyclic response of testing materials here are discussed in terms of stress evolutions at fractal pore phases and through relating sand particle shape, sorting, and mean size to soil packing state parameters. Global void ratio is idealized into micro- and macro-pore level void ratios and the impact of silt and fibre content variation on packing quality, likelihood of particle contact destruction and reorientation, and inter-particle stress evolution are discussed in length. As such, this work employs a micro-to-macro approach in studying the cyclic response of geocomposite systems.

1.3 Fibre-reinforced systems

The use of fibres for ground improvement origins from the principles of naturally reinforced soils by tree root systems. It is now well established that randomly distributed fibres in sand generally improves the drained and undrained mechanical properties of soils, including shear strength and bearing resistance (Sadek et al. 2010; Kutanaei and Choobbasti 2016; Mirzababaei et al. 2017). An important early contribution to the dynamic response of fibre-reinforced sand systems is the work of Noorany and Uzdavines (1989). They reported findings from a programme of cyclic triaxial tests and discussed the liquefaction resistance of saturated sands reinforced with a suite of reinforcing elements including fine steel-wire mesh, polypropylene fabric, nylon netting, and fine polypropylene fibres. For all fibre types, they reported an improvement in liquefaction resistance. The closing of the 20th century saw a hike in experimental dynamic studies on fibre-reinforced soils. Maher and Woods (1990) studied the anisotropy in fibre reinforced sands through a programme of torsional shear and resonant-column tests. They showed the advantages of fibres in improving the dynamic shear modulus of sandy soils. A particularly distinctive feature of fibre-reinforced soils is the anisotropic behaviour they may demonstrate under various loading conditions (Diambra et al. 2010; Gao and Zhao 2013). Most recently, Ghadr et al., (2019) and Ghadr (2020) showed that upon fibre reinforcement, the contractive behaviour of saturated loose sands - that is predominant as the inclination angle of the principal stress increases beyond 60° - changes to dilative. They also showed that the undrained performance for fibres are poor when soil carries a combination of torsional and compressive stresses. The undrained performance of fibres improves when soil carries a combination of extension and compressive stresses. The undrained performance of fibres is maximum when soil carries a combination of extension and torsional stresses, and further enhances with principal stress direction increments. Maher and Ho (1993) studied the behaviour of fibre-reinforced cemented sands under cyclic loading and reported enhanced cyclic strength upon fibre addition. Ibraim et al. 2010 and Liu et al. 2011 attributed that improvement to the role of fibres in restricting lateral movement of particles. This brings the question of fibre shape, dimensions, and texture, and how and if these play a role in soils dynamic behaviour. Li and Ding (2002) used discrete crimped polypropylene fibres and suggested that fibre content (in sand) and small-strain stiffness are directly correlated. They suggested that fibre reinforcement leads to a decrease in static flow and liquefaction potential. Their observations were later repeated and confirmed for both compression and extension loading environments (Ibraim et al. 2010; Ghadr and Bahadori 2019). Michalowski and Cermák (2002) casted doubts on the effectiveness of fibre reinforcement in sands with relatively finer particle size and angular shape. At the extreme end of angularity and silt size and for liquefiable fly ash, Boominathan and Hari (2002) showed an increase in liquefaction resistance as fibres provide enhanced interlocking, which then leads to a decrease in the excess pore water pressure. More recently, Noorzad and Amini (2014) reported similar findings but argued that advantages are more pronounced in soils of medium density as compared to loosely compacted soils. This can be a serious drawback to the stability of fibre-reinforced sands and is a principal objective of the present work.

2. Materials and Methods

2.1 Materials

Two angular sands of varied mean diameter are used in this study. Sand A is moderately-well-sorted standard F161 (Firoozkuh 161) sand with particle sizes ranging 0.80 to 1.18 mm. A UB200i Lacet transmitting light microscope (integrated with DCM-900 digital camera) was used to capture the sand particles' shape through two benchmark sphericity (r_s) and roundness (r_r) parameters in compliance with the Wadell (1932) method. Sphericity (r_s) is a measure of convergence of particle's dimensions in the three-dimensional coordinate system. Particles with the highest sphericity contain minimum eccentricity and platiness. Roundness (r_r) is a measure of surface features, relative to the radius of the particle. Angular particles typically gain small roundness index values. The size, shape and packing properties of Sand A ($r_s = 0.6, r_r = 0.38, D_{50} = 0.27\ mm, C_u = 1.78, e_{min} = 0.548, e_{max} = 0.874$) is nearly identical to those of standard Ottawa C109 sand ($r_s = 0.69, r_r = 0.40, D_{50} = 0.37\ mm, C_u = 1.80, e_{min} = 0.503, e_{max} = 0.811$) and also has some resemblance with standard Fraser River and Hostun RF sands (Gue and Su 2007; Cho et al. 2006). The second sand material investigated (Sand B) was well-sorted standard Firoozkuh 141 (F141) Sand, with particle sizes ranging 0.80 to 1.18 mm. Sand B is generally coarser than Sand A with almost similar shape properties. The size and packing properties of Sand B are brought in Table 1 ($D_{50} = 0.48\ mm, C_u = 1.16, e_{min} = 0.587, e_{max} = 0.892$). X-Ray Fluorescence (XRF) analysis on both sands confirmed their predominantly siliceous composition (SiO_2 > 96%, Fe_2O_3 = 0.2-0.7%, Al_2O_3 = 0.5-1.6%, CaO = 0.2-0.5%, Na_2O = 0.03-0.08%, K_2O = 0.03-0.10%).

The sands were mixed with a sharp non-plastic silt soil produced in-house by controlled grinding of Sand A. Fig. 2 illustrates the particle size distribution, shape, and texture of silt and sand materials. Table 1 summarizes the geometrical and physical properties of sand, silt and fibre. A common and commercially available thermoplastic polymeric micro-synthetic fibre with a ribbed linear texture (to improve adhesion with surrounding soil) and wave-shaped cross-section was adopted as the reinforcement components (MEX200, also Fig. 3). This fibre is commonly used in the construction industry, primarily as tension-resistant elements in concrete. Fibres used were 15 mm in length (l_f) and 0.20 mm in equivalent diameter (D_f), with a tensile strength of 450 MPa, ignition point of 450°C and melting point of 160°C. The adopted dimensions bring the fibre aspect ratio for reinforced systems ($AR_F = l_f/D_{50}$) within the range reported in previously published research (e.g. Ghadr et al. 2019). The upper-bound and lower-bound value for fibre aspect ratio are recommended as 100 (Shukla 2017) and 10 (Diambra and Ibraim 2015); This is to ensure reasonable levels of interaction between soil and reinforcement elements. The AR_F for fibres in the present work is in between the two extreme boundaries. The specimen aspect ratio (i.e. ratio of test specimen diameter to the length of fibres, $AR_S=D/l_f$) in fibre reinforced systems conventionally varies between 0.17 and 10.2. For example and for compacted silty clay loams, Ang and Loehr (2003) suggested an optimum 1.25 specimen aspect ratio based on strength and stress-strain behaviour and following a series of unconfined compression tests. The AR_F and AR_S for test specimens are reported in Table 1.

Table 1 Geometrical and physical properties of testing specimen constituents

Figure 2. Particle size distribution, shape, and texture of silt and sand particles

Figure 3. Illustration of fibres used in this study

2.2 Equipment

A pneumatic controlled cyclic triaxial testing apparatus manufactured by the British manufacturer VJ Tech was employed to conduct the experimental investigation and to evaluate the large-strain dynamic properties of clean sands and sands in mixtures with silt and fibre. The equipment generates dynamic frequencies in the range of 0.01 Hz to 2.00 Hz using a pneumatic pressure system. The system is controlled by digital Servo Controller which provides 16-bit resolution with an analogue and digital filter, for high and low frequencies respectively. The test settings were assigned using a Computer-Aided Testing System (CATS) software (VJTech Dynamic Suite 1.7). A solenoid valve and Swagelok controller control the cell and back pressures. A 5 kN external load cell is attached to a ram and allows measurement of applied axial dynamic loads. A linear variable differential transformer (LVDT) transducer is integrated into the actuator and allows the precise monitoring of axial displacements at 0.001 mm precision and within a +/- 40 mm range. The equipment includes three standard pressure transducers to measure the variation in cell pressure, pore water pressure and backpressure. The pressure transducers have the capacity of 1000 kPa and a sensitivity of 2 kPa (+/- 0.2% accuracy). Figure 4 shows a front and rear view of the triaxial machine used in this study.

Figure 4. The pneumatic cyclic triaxial machine [a] front view, [b] rear view

2.3 Specimen preparation

For the purpose of triaxial tests, the soil is conventionally placed in split moulds in moist, dry or saturated state; it can be placed by dry deposition, water sedimentation, pouring or spooning; or can be compacted by tapping, tamping, or vibration (Consoli et al. 2005; Soriano et al. 2017; Mirzababaei et al. 2018). Dry sands were first mixed with sharp silt measuring 0%, 10%, 20%, 30%, 40% and 50% by dry mass in a container and a small amount of water; subsequently, the requited amount of polypropylene fibres was added to the wet mix and they were thoroughly mixed. Moistening the silty sand (Hyde et al. 1993; Sadeghi and Beigi 2014; Ye et al. 2017) prior to addition of fibres is commonly used by many previous workers to avoid segregation and floating of fibres, also to facilitate the even distribution of fibres in soil. In the present study, water content was brought up to 1.5 to 2.5%, which almost equals the hygroscopic moisture content. Fibre content was varied from 0 to 1.5% in increments of 0.5%. The concentration of fibres included in a composite is defined as a proportion of the dry weight of soil, $\chi = W_f / W_s$, where W_f is the weight of fibres and W_s is the weight of the dry soil. The adopted range of fibre contents here accommodates the optimum fibre content of 0.3% to 0.5% reported in previous studies (Hoare 1979; Mercer et al. 1984; Al-Refeai and Al-Suhaibani 1998; Ghadr et al. 2019; Ghadr 2020). For Sand B, a 1.0% maximum fibre content was adopted for testing due to some operational constraints. Fibres were added ‘randomly’ to the mix in small, equal, and controlled amounts. The split mould (i.e., sample former) sized 50 mm in diameter and 100 mm in height. The adopted diameter to height ratio complies with the ASTM D3999-91 recommendations. A small amount of body powder (hydrated magnesium silicate) was applied to the edges of the sample former; The two halves of the sample former were then secured against one another by placing and tightening a clamp. A membrane was placed over the base pedestal and fixed in place with an O-ring. The excess membrane was then folded up over the O-ring before a second O-ring was placed over the base pedestal and rolled just above the first O-ring. The free top of the membrane was folded over the sample former. A small vacuum pressure of 15 kPa was applied to two points around the perimeter of the split mould to stretch the membrane against the inner wall of the former. Sand-fibre mixtures were poured into the split mould resting on a flat working surface and total mass of mixture contained in mould was measured. The mixture was decanted, divided into five equivalent parts, and carefully poured into the split mould fixed on the lower porous disc on the platen (i.e., base pedestal) of the triaxial cell in five layers. Dry mixtures were poured through a funnel with a nozzle opening of 25 mm in diameter into the former in sequential layers. The initial void ratio was kept at the natural high, but low enough to minimize the entanglement and distortions in slender fibres potentially caused by the large compaction effort needed in the case of high fibre content (Gray and Ohashi, 1983).

A loading cap was placed on the top of the specimen and the split mould was the removed whilst a small 14 to 15 kPa vacuum pressure was applied through the back pressure and upper outlets to allow the sample to maintain its cylindrical shape after the moulds were removed. The pressure chamber was assembled. Afterwards, a small cell pressure of 50 kPa was applied through the hydraulic devices, and the vacuum pressure was simultaneously released.

The initial void ratio of metastable samples is reported in Table 2 and marked as e_0. Gaseous CO_2 and de-aired water were then gently introduced through the bottom drainage to the soil specimens and were driven upwards through the specimens. Pore water pressure and cell pressure were then increased simultaneously and in equal increments to raise the B-Skempton value to 0.96 at which state soil was deemed fully saturated. Depending on the silt content, the time required to accomplish saturation ranged from 30 min to 5 hours. Specimens were then isotopically consolidated to a range of initial void ratios (e_c in Table 2) under a constant 200 kPa initial confining pressure (here reported as initial effective mean principal stress, P'_c). The e_c fell in the range of 0.44 to 0.81 for unreinforced Sand A and 0.40 to 0.88 for unreinforced Sand B. A harmonically varying cyclic load was applied to the saturated specimens during the cyclic axial test, and the variation of excess pore water pressure and axial stress and strain of the specimen were continuously recorded during cyclic loading.

Table 2 summarises the 41 triaxial specimens tested in this study, their initial mean effective stress, initial and post-consolidation global void ratio, idealised void ratios, fine content (FC) and fibre content. Each specimen is numbered and given a test ID. The first letter indicates the sand type, silt content is indicated in brackets, followed by the fibre content in per cent; for example, A(20):1.5 stands for Sand A mixed with 20% by mass silt and 1.5% fibre. The CSR is the cyclic stress ratio; that is the ratio of the cyclic deviator stress (σ_d) to the initial confining stress, P'_c, $CSR = \sigma_d / 2P'_c$. In this study, the CSR was set at 0.15, which corresponded to deviator stress of 60 kPa. The relatively small CSR makes the influence of fibre content more remarkable (Ye et al. 2017), avoids additional compaction induced by cyclic loading-unloading (Sadeghi and Beigi 2014), and allows the relative loose testing specimens here to reach the state of liquefaction (Xu et al. 2015). A sinusoidal waveform loading with the frequency (f) of 0.05 Hz was applied on the specimens until liquefaction occurred. Typical traffic load frequencies fall within the 0 to 10 Hz range (Hyde et al. 1993) whilst a range of 0.1 to 1.5 Hz is well established for the cyclic loading frequency in most geotechnical problems and broadly applied by many experimental workers (Al-Refeai and Al-Suhaibani, 1998; Ye et al. 2017). The choice of low frequency is consistent with the relatively open packed porous state of test specimens. The liquefaction onset was considered as the mean effective stress when first reaching the zero-stress state, that is when the generated excess pore water pressure ratio was equal to or higher than 0.96. Here, we employ a parameter N_l, which is defined as the cycle number at which the excess pore water pressure ratio first reached 1.0 to indicate the loading cycle number for triggering liquefaction. In this, larger values of N_l corresponds to greater resistance to liquefaction in the sand. Table 2 summarises the achieved values of N_l; these fell in the range of 3 to 19 for unreinforced Sand A and 7 to 52 for unreinforced Sand B. The excess pore water pressure ratio is presented in Table 2 with r_u and is defined as $r_u = \Delta u / \sigma_3$, where Δu is the excess pore water pressure.

Table 2 Testing itinerary and specimens (f=0.05 Hz, CSR= 0.15, σ_d= 60 kPa)

3. Scale-dependent Porosity

Packing density is a macro-scale parameter measured via the specimen mass and volume (Fonseca et al. 2013) and is the fraction of the total packing volume occupied by solid particles in a domain of soil. For example, for an assembly of particles with a void ratio of 1.0, the packing density is about 0.5. Packing density is commonly quantified using the de Larrard (1999) equation as a function of packing density of soil components (hear sand and silt), solid volumetric fraction of less dominant fraction (here silt) and interaction functions that are directly correlated with particle size ratio (i.e., the ratio of mean particle size of dominant, to less dominant soil component). Metastable granular materials can generally adopt two random structures: The Random Loose Packing (*RLP*) and the Random Close Packing (*RCP*). For granular materials containing monodisperse spheres, the RLP quality occurs at void ratios above 0.6. The RCP quality occurs at global void ratios between 0.5 and 0.6 (Xu et al. 2015). Void ratios lower than 0.5 represent Close Packing (*CP*) quality that occurs in most natural soils. In Table 2, for Sand A, irrespective of fibre content, consolidated soils adopted an *RLP* state (with a packing density of around 0.539) for 20% fine fraction (FC). As the fine fraction increases to 40%, the packing state changes to *RCP* (with a packing density of around 0.690). With further increase in fine fraction to values above 40%, soil adopts a close packing state (i.e. dense state). In this and for Sand A, the 40% fine content marks a critical transition point from a metastable random packing to a stable close packing (CP). For Sand B, the metastable *RLP* state changes to stable *CP* at the slightly lower 30% fine fraction. The threshold silt content appeared in the form of a dip in the minimum global void ratio (e_{min}) plot against silt content in Figure 5 for Sand A. The two extreme void ratio values (e_{max} and e_{min}) are effectively density related indices that limit them physically attainable void ratios in binary granular materials.

Figure 5. Minimum and maximum void ratios for sand-silt composite mixes

To better understand the links between the packing state and fines content, the pore phase is idealised as micro- and macro-pore spaces. The testing material here ranges from pure sand to sandy silt; As such, only trans-assemblage (macro) and inter-assemblage (micro) void spaces are likely to form the soils' void structure. Equations 1 to 4 formulate the void ratio at the macro (e_s) and micro (e_f) scale using formulations proposed in Thevanavagain and Mohan (2000), and Thevanayagam (1998). The method is also discussed in Bouckovalas et al. (2003), Thevanayagam and Martin (2002), Xenaki and Athanasopoulos (2003), and Yang et al. (2006).

$$e_s = \frac{e_c + (1 - b_i)FC}{1 - (1 - b_i)FC} \tag{1}$$

$$e_f = \frac{e_c}{FC + \frac{(1 - FC)}{{R_d}^m}} \tag{2}$$

where e_c is the global void ratio at the end of the triaxial consolidation stage, FC is the fines content, m is the improvement factor that ranges from 0 to 1, and the parameters R_d (the size disparity) and b_i are defined as follows.

$$R_d = \frac{D_{50(sand)}}{D_{50(silt)}} \tag{3}$$

$$b_i = \left(1 - {e_c}^{-\left[n\frac{f^n}{1-r^{0.25}}\right]}\right)(r\frac{FC}{FC_t})^r \tag{4}$$

$$m = log\left(\frac{111 - 91b_i}{11 + 199b_i}\right) \tag{5}$$

where $D_{50(sand)}$ and $D_{50(silt)}$ are the mean particle sizes of the sand and silt fractions, respectively; FC_t is the threshold fines content, f is the loading frequency, parameter n governs the initial rate of increase in b_i with increasing FC, thereby $n = \partial b_i/\partial FC$, and $r = D_{50(silt)}/D_{10(sand)}$, where $D_{50(silt)}$ and $D_{10(sand)}$ are the mean and effective particle sizes for the silt and sand fractions, respectively. Note parameter b_i represents the relative effectiveness of the soil's fine fraction in carrying interparticle stresses (i.e., the contribution of separating fines to active contacts,($0 < b_i < 1$). The b_i magnitude directly proportional to the fines content.

Figure 6 illustrates the variation with silt content of trans-assemblage and inter-assemblage void ratios for Sand A. Immediate observations suggest that silt content is inversely proportional with the inter-assemblage pore void ratio (e_f) and directly proportional to the trans-assemblage void ratio (e_s). In other words, for a silty sand soil and for silt contents lower than the threshold, an increase in silt content leads to a substantial decrease in micro-scale void ratio. This indicates the tendency of silt to coagulate into silt globules, a consequent decrease in micro-scale pore size and increase in matric suction. Fibre reinforcement generally decreases the global void ratio (Fig. 6a) but has little effect on idealised void ratios.

The idealisation of void spaces was recently explored for binary sand-clay mixtures in Ghadr and Assadi-Langroudi (2018). They discussed the fractal pore phases in the context two conceptual *Small Clay* and *Large Clay* models and through relating sand particle shape, sorting, and mean size to soil packing state and hydromechanical properties. Building on those findings, two conceptual models are proposed for the sand-silt mixtures: *Small Silt* and *Large Silt*. At low silt contents (fine fraction below 40% - here termed as *Small Silt*), the variation of silt content has little effect on trans-assemblage and substantial effect on inter-assemblage pore spaces (Fig. 6b). On addition of silt, trans-assemblage void spaces marginally expand in volume. Silt initially sits at sand-sand contact trapdoors and form silt aggregates, pushing sand grains apart and expanding the trans-assemblage void space: Initially, silt assemblages are loose and honeycomb in shape. As silt content increase, additional silt particles rest in the intra-lattice space within the honeycomb aggregates. This leads to the gradual transformation of the loose silt pellets to densely packed, tightly interlocked silt coagulates. This explains the inverse relationship between silt content and inter-assemblage void ratio (for *Small Silt*). For *Large Silt* systems (silt fraction above 40%), the variation of silt fraction has little effect on inter-assemblage pore spaces and substantial effect on trans-assemblage pore spaces. As silt content increase, densely packed silt coagulates expand into and occupy the trans-assemblage pore phase. With an exception of soils with $FC < 10\%$, fibres appear to have almost no influence on post-consolidation inter- and the trans-assemblage void ratio at high silt contents. In determination of void ratios at the end of consolidation (that account for densification during saturation and consolidation), fibres were treated as being part of the solid in calculations. This is a consistent approach with the recent similar experimental attempts (e.g. Zhang and Russell 2020).

Figure 6. (a) Global void ratios for sand-silt-fibre mixtures [Sand A] (b) intergranular and inter-fine void ratios for sand-silt-fibre mixtures [Sand A]

4. Results and Observations

A total of 41 cyclic triaxial experiments were conducted in this research in compliance with ASTM D5311 standard. The excess pore water pressure ratio (r_u), axial strain (ε_c) and axial stress (σ_d) were measured at regular periodic intervals during the course of cyclic sinusoidal waveform load application. The load was retained on specimens until the initial liquefaction when the r_u became equal to 1.0. Findings from a typical cyclic triaxial experiment conducted on A(0):0 (see Table 2) are presented in Fig. 7a-e. The development of strains with growing cycles is not uniform. This is clear in Fig. 7a, where the greatest strain increments appear to have taken place with a distance from the core of stress-strain loops. This suggests that liquefaction failure in unreinforced granular soils is a sudden phenomenon with not much early warning in the form of ground movements. In Fig. 7a and for the initial cycles, the hysteresis loops adopt an ellipse shape with narrow width and sharp corners that mark sharp load reversal events. This implies a viscoelastic behaviour. The hysteresis loops become wider and adopt a parallelogram shape with further loading/unloading cycles. The variation of ε_c and cyclic deviator stress is minimal during the early stages of cyclic loading (Fig. 7d). The excess pore water pressure however gradually and constantly grows with an increasing number of loading cycles. The r_u sharply increases from 78% to 93% and the axial strain begins to rise at the 16th cycle of loading. On the 18th cycle, the r_u tends to nearly 1.0 (Fig. 7b) and the axial strain gains a double amplitude axial strain of about 5.5%, indicating a complete state of liquefaction (Fig. 7c). At this stage, the stress state is likely to have touched the failure envelope.

Figure 7. (a) stress-strain relationship for A(0):0, Time histories of (b) excess pore water pressure ratio, (c) Axial strain, (d) deviator stress, (e) Effective stress path for test specimen 1 (pure sand)

4.1 Effect of fine fraction and underlying micro-mechanisms

The core objective of this study is to gain a better understanding of the impact of non-plastic fines and fibres on dynamic properties of loose saturated sands. The excess pore water pressure ratio (r_u) and the number of cycles required to cause initial liquefaction (N_l) are adopted as benchmark parameters that quantify the liquefaction potential. The formation and growth of excess pore water pressure under undrained loading conditions is well-established as the fundamental mechanism related to liquefaction. Initial liquefaction happens when excess pore water pressure ratio (r_u) reaches 1. The general $r_u - N$ trends for two sands were found to be similar. For Sand A, the excess pore water pressure ratio is plotted against the number of loading cycles in Fig. 8 for CSR =0.15 and unreinforced silty sand specimens.

Figure 8. Pore pressure response against loading cycles for unreinforced silty sands [Sand A] and CSR =0.15

Initial inspection of Fig. 8 suggests that the rate of pore pressure generation in the sand–silt mixtures are generally higher than that of clean sand. It is clear that the development of r_u with loading, cycles are dependent on the fines content, with two explicitly different patterns seen for fines content lower and higher than a critical threshold (FC_t). The fundamentals of this critical fines content threshold were earlier discussed in Fig. 1 and Fig. 6.

A combination of contact destruction and contact reorientation events lead to the progressive weakening of the contact force network until it becomes insufficient to sustain any further shearing at which point soil experiences large deformations and liquefies. Xu et al. (2015) recently highlighted the dominant role of inter-particle friction as the governing micro-parameter for liquefaction resistance. These fundamental concepts are discussed here in the context of the conceptual *Small-Silt Large-Silt* model, a graphical illustration of which is presented in Fig. 9.

Figure 9. Conceptual idealised void spaces model for sand-silt mixtures: transition of packing quality with increasing fines content

For fines content lower than FC_t (*Small Silt*), loose honeycomb silt pellets appear at sand-sand contact points. In Table 2, the average coordination number for Small Silt soils is generally low, leading to a greater likelihood of carrying the higher interparticle stresses (McDowell and Bolton 2000). Here, the coordination number (CN) is a scalar fabric quantity and a measure of the number of contacts per particle (Thornton 2000; Fonseca et al. 2013) used to link the macroscopic behaviour to the changes in the microstructure. The parameter was first formulated by Smith et al. (1929) as a function of void ratio. Ode 1977 and Nolan and Kavanagh 1992 presented extensive experimental data to correlate the coordination number with the void ratio in two- and multi-mixed particulate assemblies. Assadi-Langroudi et el. 2018 showed that the Smith and colleagues' equation is in excellent agreement with the experimental equations of Ode 1977, once the void ratio is set to the idealised values. Increasing silt content up to FC_t leads to the densification of silt pellets with little impact on trans-assemblage void spaces. This has a number of implications. Silt pellets interfere with the interlocking of sand particles at sharp contact points, leading to a decrease in inter-particle friction. Silt pellets act as lubricating agents and facilitate displacement of sand grains with increasing loading cycles. In other words, stronger pellets function as hinge elements with trapdoor effect, allowing sand particles to roll over one another. Initially, contact destruction is limited mainly due to the isotropic consolidation. Contact destruction then rapidly gains momentum with increasing cycles. Increasing fines content forms more competent silt pellets which further facilitates rotation of sand particles within the trans-assemblage void phase, their clashing and destruction. This has reflected in the faster growth of r_u at higher fines content in Fig. 8 for *Small Silt* soils. For silty sands with fines content greater than FC_t (Large Silt), the excess fines expand into the trans-assemblage void space, increase the coordination number (see Table 2) and decrease the average skeletal force magnitude. The excess fines at macro-voids act as cushions, damp the energy and provide a degree of additional support to sand particles. Increasing silt content beyond FC_t leads to a decrease in contact destruction. This has reflected in the slower growth of r_u at higher fines content in Fig. 8 for *Large Silt* soils. Soil develops a greater potential of liquefaction with increasing fines content to a limiting $FC_t = 40\%$ (common in both sands as seen from the $N_l - FC$ pattern in Table 2). Any further increase in fines content would decrease the liquefaction potential.

4.2 Effect of fibre inclusion and underlying micro-mechanisms

For both sands, the number of cycles to liquefaction (N_l) increase with increasing fibre content. For clean Sand A, the N_l increased approximately 2.4 times from 19 in A(0):0 to 46 in A(0):1. The increase in N_l for Sand, A is remarkably greater than in clean Sand B, where the N_l increased approximately 1.2 times from 62 in B(0):0 to 80 in B(0):1. Whilst this may imply the greater efficiency of fibre reinforcement in sands of relatively lower median size, it is important to take note of the substantially lower [potential of clean coarse Sand B as compared to Sand A.

Figure 10 plots the evolution of r_u with the number of loading cycles towards initial liquefaction for isotopically consolidated fibre-reinforced sand mixtures (Sand A) at a confining pressure of 200 kPa. Important observations are made here. First, the addition of fibres seems to have decreased the r_u. This is a welcomed phenomenon and in agreement with earlier findings (e.g. Ye et al. 2017), where the rate of increase of the excess pore water pressure was reported to become lower with the increment of fibre contents. Whilst r_u gains value with increasing loading cycles, rapid sawtooth fluctuations in the $r_u - N$ sinusoidal curves reflect rapid contact reorientation events which theoretically last until particles attain a more stable state. Relatively stronger fluctuations can be seen in soils with lower fibre content at any N cycle. This lends evidence to the encrusting role of fibres as they brace the trans-assemblage pore spaces and arrest contact reorientation. It is also evident that with the application of constant cyclic stress, r_u only increases after a certain number of cycles (let this be N_1) before increasing dramatically towards the first liquefaction event. The N_1 is directly correlated with fibre content. This infers that unlike unreinforced sands, liquefaction in reinforced sands is not sudden and can easier be detected at early stages.

Figure 10. Effect of fibre content on the progress of excess pore water pressures (a) Clean sand (b) F161 Sand A + 10% silt (c) Sand A + 20% silt (d) Sand A + 30% silt (e) Sand A + 40% silt (f) Sand A + 50% silt (for a constant CSR= 0.15).

Small Silt

In Fig. 11 and for mixtures with $FC = 20\%$ (*Small Silt* – Sand A), the global, micro- and macro-scale void ratio only marginally vary with increasing fibre content. For 0% to 1.5% fibre content, $e_f = 1.48 \pm 0.01$, $e_s = 0.86 \pm 0.01$ and the packing adopts a global void ratio of $e = 0.58 \pm 0.01$. For fines content lower than the threshold FC_t, the coordination number and the liquefaction resistance increase with increasing fibre content. This is evident in Table 2 and from the inverse relationship between N_l and fibre content in specimen Nº 3, 9, 15 and 21. Here, N_l sees an increase from 11 to 34 with increasing fibre content (to 1.5%). Similar trends for Sand B (specimen Nº 27, 33, 38) followed, although as in the case of clean sands, the increase in N_l was found to be moderate. One should also note that unlike in Sand A, the global and idealised void ratios exhibit a more marked decrease on fibre addition to Sand B mixed with 20% silt content (representing *Small Silt*). In Fig. 11 and for mixtures with $FC = FC_t = 40\%$ (limiting or threshold fines content) and for 0% to 1.5% fibre content, the global void ratio varies only marginally and adopts a mean $e = 0.45 \pm 0.01$ value. At that constant global void ratio, increasing fibre content leads to a modest 2.8% decrease in macro-scale void ratio from $e_s = 1.086$ to $e_s = 1.055$ and a more substantial 4.0% decrease in micro-scale void ratio from $e_f = 0.846$ to $e_f = 0.812$. This suggests that fibres tend to sit deep into silt pellets and encrust the trans-assemblage void spaces. Increasing fibre content leads to an increase in the average coordination number (see Table 2), a decrease in contact forces, a decrease in contact destruction and consequently enhanced liquefaction resistance. The encrusting fibres also generate some degree of dilation which then leads to a decrease in excess pore water pressure ratio (see Fig. 10). Lower liquefaction potential is evident for Sand A in Table 2 and from the inverse relationship between N_l and fibre content in specimen Nº 5, 11, 17 and 23. Here, the N_l sees an increase from 3 to 13 with increasing fibre content. Similar to Sand A, the N_l increased with increasing fibre content in Sand B specimens mixed with the threshold $FC_t = 40\%$ silt content.

Figure 12 illustrates the first and second stress-strain hysteresis loops for A(0):0, A(20):0 and A(20):1.5 (Fig. 12a) and B(0):0, B(20):0 and B(20):1.0 (Fig. 12b) for *Small Silt* specimens. In all classes, silt content is 20% which brings the soils into the *Small Silt* category specimens. Larger strain increments in Sand B specimens is consistent with generally greater N_l (i.e. number of cycles to liquefaction) and hence flow resistance in sands with coarser grain size. This is mainly attributed to the higher gravitational forces at the particle level and a greater degree of direct sand-to-sand interlocking. Larger strains also imply a generally less sudden and mode gradual increase in axial strains in sands with coarser grain size. Reinforcement of Sand B with fibre continue to increase the axial strain for each loading cycle as in Sand A, but to a more moderate level. This is in conjunction with the trend of N_l with fibre content in Table 2 suggest a lesser efficiency of fibres for sands of larger median diameter.

The rigid wall boundary effect

An interesting observation here is the peculiar trends of global and idealised void ratio variation with fibre content in fibre reinforced Sand B specimens. At threshold fine content, both types of void ratio increased with increasing fibre content from 0.5 to 1.0% (see Specimen Nº 35, 40). Among the idealised void ratios, the increase is more pronounced at the micro-pore level (i.e. e_f). For fibre-reinforced coarse sand at threshold silt content, this implies disturbance of dense silt pellets upon further addition of fibres, which then probably has led to the migration of liberated fines to new accumulation sites at fibre-to-sand and fibre-to-fibre contact points. This is quite speculative, and confirmation of such events does need advanced imaging, which in the case of non-cohesive sands in technically very hard. Similar trends were observed for Sand B at $FC = 50\%$ (*Large Silt* system). It appears that the presence of fibres in the coarser Sand B has a substantial impact on the porosity in their vicinity. Events here may relate to the ‘rigid wall boundary effect', in which particulate matters (here large sand particles) near a rigid wall boundary (here fibres) develop higher local porosity. The radius of this 'perturbed zone' where fresh pellets of silt form is estimated between 10% (De Larrad 2014) to 100% (Soriano et al. 2017) of average sand size in fibre-reinforced sand systems, whilst this radius theoretically can be as large as 4 to 5 times average particle size diameter (Suzuki et al. 2008). Observations here demand further investigation. Given the small size of the dataset here, findings cautiously suggest that the efficiency of fibre reinforcement in *Large Silt* system may be compromised when the median size of sand increase beyond a certain critical value. Identification of that critical sand size is significantly important but remains out of scopes of this study.

Large Silt

In Fig. 11 and for mixtures with $FC = 50\%$ (*Large Silt*), and for 0% to 1.5% fibre content, the global void ratio varies only marginally with a mean $e = 0.43 \pm 0.01$ value. At that constant global void ratio, increasing fibre content leads to a modest 3.2% decrease in macro-scale void ratio from $e_s = 1.307$ to $e_s = 1.275$ and a more substantial 4.2% decrease in micro-scale void ratio from $e_f = 0.713$ to $e_f = 0.683$. Similar underlying mechanisms to the $FC = FC_t$ the case applies here. The direct correlation between the liquefaction resistance and fibre content ties in with the inverse relationship between N_l and fibre content in Table 2.

Figure 11. Variation of void ratio with the number of loading cycles to liquefaction (a) global void ratio (b) skeletal void ratio (c) Fine void ratio

Figure 12. The stress-strain relationship for Sand A and B at FC=0% and FC=20% in unreinforced and reinforced forms (a) Sand A, (b) Sand B

Shear modulus

The secant shear modulus (G) is determined in compliance with methods proposed by Kokusho 1980 and through analysing the second hysteresis loop curves. In reflection of the cycle number, the shear modulus is presented here with G_2 and plotted against fines content in Fig. 13.

Figure 13. Effect of fines and fibre content on shear modulus

Similar to the r_u, the shear modulus (G_2) decreases with increasing fines content for *Small Silt* soils, which can be attributed to the contractive behaviour of silty sands (Fig. 9). Similar findings were reported for clayey sands in Sadeghi and Beigi 2014 and $\chi(=0, 0.5, 1\%)$. To bring this observation in numbers, for Sand A, the percentage increase in the 2nd cycle shear modulus corresponding to 0.5%, 1% and 1.5% fibre content amounted to 11%, 28%, and 46% respectively. For Sand A mixed with 30% fines content (*Small Silt*), the increase in G_2 corresponding to 0.5%, 1% and 1.5% fibre content amounted to 537%, 881%, and 1405% respectively. Findings here are consistent with earlier findings in Maher and Woods (1990) and Noorzad and Amini (2014) for fibre-reinforced cohesionless soils.

5. Conclusions

Key findings are summarised below.

1. For both reinforced and base soils, the initial Random Loose Packing (RLP) state change to a Random Close Packing (RCP) as silt content is increased beyond 20%. The metastable random packing changes to a stable Close Packing (CP) state as silt content in further increased beyond 40%. The latter transition accounts for the transition from *Small Silt* to *Large Silt* system and takes place at a lower threshold silt content in coarser sands.
2. In a silty sand system and for silt contents lower than the threshold (*Small Silt* system), an increase in silt content leads to a substantial decrease in micro-scale void ratio. Loose silt pellets gradually transform into densely packed, tightly interlocked silt coagulates. Formation of silt coagulates leads

to a gradual expansion of sand structure and the macro-pore space volume. The consequent decrease in micro-scale pore size leads to a gradual increase in the matric suction.

With an exception of soils with $FC < 10\%$, fibre reinforcement generally decreases the global void ratio but has little effect on idealised void ratios and hence water retention capacity of the soil system.

3. Variation of global and idealised void ratios with fibre content in fibre reinforced sandy specimens and when the sand of a larger median diameter was used follows peculiar trends that signify the importance of sand size. Findings cautiously suggest that the efficiency of fibre reinforcement in *Large Silt* system may be compromised when the median size of sand increases beyond a certain critical value. Identification of that critical sand size is important but remains out of scopes of this study.
4. Liquefaction failure takes place following a combination of contact destruction and contact reorientation events that lead to the progressive weakening of the contact force network, until interlocking at particle-to-particle contact points become insufficient to sustain any further shearing at which point soil experiences large deformations, flow and liquefaction. In unreinforced silty sands, failure is sudden with not much early warning in the form of ground movements.
5. The impact of fines content on the $r_u - N$ interplay is explicitly different between *Small Silt* and *Large Silt* systems. A micro-to-macro approach is adopted here.

As silt pellets gain strength, the interlocking between sand particles and hence inter-particle friction decreases. Silt pellets facilitate displacement of sand grains and hence contact destruction with increasing loading cycles. At macro-scale, this leads to faster growth of r_u with N at rates greater than those in clean sand systems. On further addition of silt to silty sand and as silt content increase beyond the threshold, silt pellets expand to macro-void phase to increase the coordination number, damping, and overall resistance of sand grains against contact destruction. At macro-scale, this leads to slower growth of r_u with N with increasing silt content.

The mechanisms discussed here can be extended to any natural hazard that involves in a sudden flow of muddy waters into sandy grounds, riverbanks and hillslopes, and explains how the interplay between independent events such as earthquake, debris flow and liquefaction can cause interacting problems.

6. Irrespective of fine content, fibres tend to sit deep into the silt pellets and encrust the trans-assemblage void spaces. At the micro-scale, footprints of the hypothesised encrusting (bracing) function of fibres at trans-assemblage pores were found on the $r_u - N$ envelope and in the form of rapid sawtooth fluctuations that mark rapid contact reorientation events. Increasing fibre content leads to an increase in the average coordination number, dilation and easier dissipation of excess pore water pressure, a decrease in contact forces, a decrease in contact destruction and consequently enhanced liquefaction resistance.

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